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IGNITION OF A LIQUID FUEL UNDER HIGH INTENSITY RADIATION.(U)  
1978 T KASHIWAGI, H R BAUM

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PROGRESS REPORT OF "IGNITION OF A LIQUID FUEL UNDER HIGH INTENSITY  
RADIATION" FROM MAY 1, 1977 TO APRIL 30, 1978

Takashi Kashiwagi

and

Howard R. Baum

Center for Fire Research  
National Bureau of Standards

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REPORT 78-1008

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PROGRESS REPORT OF RESEARCH ON A LIGHT PULSED LASER SYSTEM  
PERFORMED FROM MAY 1, 1977 TO APRIL 30, 1978

Technical Report

and

Report of Work

Center for Laser Research  
National Bureau of Standards

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PROGRESS REPORT OF "IGNITION OF A LIQUID FUEL UNDER HIGH INTENSITY  
RADIATION" FROM MAY 1, 1977 TO APRIL 30, 1978

By

Takashi Kashiwagi  
and  
Howard R. Baum

Abstract

Ignition of n-decane in the incident flux range from 800 to 4000 w/cm<sup>2</sup> was studied experimentally by using a CO<sub>2</sub> laser. Study of the effect of container size showed 6 cm diameter by 5 cm depth sufficient. The effect on ignition of the incident angle of the laser beam with respect to the decane surface was studied at 90°, 75°, 60° and 45°. The relationship between the ignition delay time and the incident radiant flux is almost the same for 90° and 75°. Reducing the incident angle to 45°, the ignition delay time becomes longer and the minimum incident flux for ignition increased significantly. The measured extinction coefficient of decane at wavenumber 946cm<sup>-1</sup> is 16 cm<sup>-1</sup>. The auto ignition mechanism of decane by a CO<sub>2</sub> laser is the absorption of the incident laser energy by the decane vapor plume.

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## 1. Introduction

Laser technology has been rapidly advancing in the last two decades. Power outputs of modern lasers increased significantly and these lasers can be used as tactical weapons. A high power laser weapon can ignite aircraft fuel through fuel tank penetration and can cause fire or explosion of the aircraft. The objective of this program is to obtain a fundamental understanding of physical and chemical mechanism of the ignition of liquid fuels under high intensity radiation.

The program consists of an experimental study to clarify the key mechanisms of ignition, and a theoretical study to predict the qualitative effects of physical and chemical parameters on ignition of flammable liquids. Since the radiative ignition of flammable liquids is hardly known, the theoretical study has been deferred until the key ignition process is confirmed from the experimental study.

In the first year of this program, the effect of the container size on ignition was studied first to determine the appropriate container size to avoid wall effects. Then, the effect of the incident angle of the laser beam with respect to the liquid surface on ignition delay time was studied. The radiative properties of the sample, such as extinction coefficient and total surface reflectance, are being measured.

## 2. Experimental Apparatus

A schematic illustration of the experimental apparatus is provided in Figure 1. Photographs of the equipment are shown in Fig. 2 and Fig. 3. A Coherent Radiation Model 41 CO<sub>2</sub> laser emits an approximately 5 mm diameter beam (at  $1/e^2$ ) whose power can be varied from 240 to 350 watts by adjusting the current through the laser discharge tube. This range of the power is selected to maintain the fundamental mode whose power distribution across the beam is Gaussian. The incident flux distribution at the sample surface position is measured prior to each ignition experiment by traversing a water cooled calorimeter with 0.25 mm sensing diameter. The maximum value of the incident flux is used as the incident radiant flux in this experiment.

A shutter, consisting of a switchable mirror, is used to provide a step-function irradiance, and remains open through the ignition event. Ignition is determined by the first light emission, which is measured by an EMI 7656 photomultiplier the output of which is recorded by a visicorder. At the onset of flaming, a step-function like output of the photomultiplier is observed. This output is used as unambiguous determination of the ignition event. In tests to date, n-decane was used as the liquid fuel and air as the environmental gas.

The experimental chamber is 34 cm inside diameter with 40 cm length as shown in Fig. 3. The chamber is mounted on bearings and can be rotated 90 degrees by a worm gear. The incident angle of the laser beam is varied by using two mirrors and by the rotation of the chamber as shown in Fig. 1. After each ignition test, the gas in the chamber is evacuated by a vacuum pump.

The setup for the measurement of total surface reflectance at various incident angles is being prepared. A schematic illustration of the apparatus is shown in Fig. 4. An ellipsoidal mirror, 31.1 cm in diameter and 9.2 cm high, is the principal feature of the design. Its focal points are located about 9.2 cm and 51.8 cm from the apex, and it has a linear magnification factor of about 5.7. The laser beam ( $\sim 5\text{mW}$ ) from a  $\text{CO}_2$  laser is modulated and irradiates the sample surface at the first focal point of the ellipsoid through a small hole in the ellipsoidal mirror. A pyroelectric detector, 1.0 cm diameter, is used to measure the reflected laser beam from the sample. At present, the calibration of the system is in progress.

### 3. Experimental Results and Discussion

The first series of experiments were conducted to find a container size which did not affect ignition delay time under various experimental conditions. The effect of the depth of the container on ignition delay time was studied with 5 cm diameter container under

the vertical radiation mode (incident angle  $\theta = 90^\circ$ ). The depth of the container was varied from 1.2 cm to 34 cm. Results are shown in Fig. 5, which indicate little effect of depth on ignition delay time except extremely shallow case. The same conclusion was also derived from experiments conducted at lower incident flux.

Similarly, the effect of the diameter of the container on ignition delay time was studied with 5 cm depth container at  $\theta = 90^\circ$  at two different incident radiant fluxes. The diameter of the container was varied from 2.5 cm to 10 cm. Results are shown in Fig. 6a at the incident radiant flux  $I_o = 4160 \text{ w/cm}^2$  and in Fig. 6b at  $I_o = 1670 \text{ w/cm}^2$ . At high flux, there is no effect by the diameter of the container on ignition delay time, but, at low flux, ignition delay time becomes significantly longer for the container whose diameter is less than 4 cm. Apparently, there are some heat losses to the container wall, which delay the ignition. From these results, a container of 6 cm diameter and 5 cm depth was selected and used for all experiments described in this report. The container is fastened onto the support plate which is mounted on the chamber wall. When the chamber rotates, the support plate tilts and the axis of the container is along the incident laser beam. To make the container top parallel to the horizontal decane surface, the top of the container is cut to be horizontal when it tilts.

During the ignition period, bursting sounds, similar to that when water droplets are dropped onto a heated plate, are clearly heard. This indicates the rapid boiling of decane after laser irradiates it. However, decane droplets were not observed outside of the container after the experiment except for extremely low incident radiant fluxes. Apparently, a large volume of decane is heated during the long ignition delay at the low radiant flux and more decane boils off. Under this condition, ignition was associated with a puff sound and the size of flame immediately after ignition seemed larger than that at high incident radiant flux.



High speed direct motion pictures (1500 frames/sec) were taken to observe the onset of ignition sample frames are shown in Fig. 7. They show the onset of flaming in the gas phase far above the decane surface the rapid flame spread toward the surface. Since boiling temperature of decane is  $174^{\circ}\text{C}$ , the gas phase temperature near the surface could go up to this temperature by conduction/convection from the decane surface. This is too low to initiate the gas phase chemical reaction and to attain a runaway condition. For this reason, it is postulated that the absorption of the incident laser energy by the vapor in the gas phase would be the key heating process to initiate the chemical reaction. This is confirmed by the ignition of vapor from decane heated by an electrical hot plate by passing the laser beam through the vapor parallel to but above the liquid decane surface. Therefore, the ignition mechanism of decane by high intensity radiation appears to be the absorption of the incident radiant energy by its vapor plume.

The relationship between the ignition delay time and the incident radiant flux were studied with various incident angles and results are shown in Figs. 8a, b, c, d. Roughly, above  $2500 \text{ w/cm}^2$ , ignition delay time increases significantly with a decrease in flux. There is a peculiar trend where ignition delay time tends to increase with incident radiant flux at high flux. This was observed at all four incident angles studied in this work. It is not clear what mechanism causes this trend. Different phenomena might occur, such as changes in boiling of decane or in the development of the vapor plume at high radiant flux. Therefore, it is planned to take high speed photographs to observe the behavior of the decane surface and to take high speed shadowgraph pictures to observe the development of the plume.

Fig. 8a, b, c, and d show little difference in the relationship between  $\theta = 90^{\circ}$  and  $\theta = 75^{\circ}$ . However, at  $\theta = 60^{\circ}$  and  $\theta = 45^{\circ}$ , the minimum incident radiant flux,  $I_{\min}$ , for ignition increases with a decrease in the incident angle. At  $\theta = 60^{\circ}$ ,  $I_{\min} \approx 1400 \text{ w/cm}^2$  and at  $\theta = 45^{\circ}$ ,  $I_{\min} \approx 1800 \text{ w/cm}^2$  compared to  $I_{\min} \approx 1000 \text{ w/cm}^2$  for  $\theta = 75^{\circ}$  and  $90^{\circ}$ .



The difference between  $\theta = 60^\circ$  and  $\theta = 90^\circ$  or  $\theta = 75^\circ$  is found only near the ignitable boundary; otherwise there is little difference between them. However, the relationship at  $\theta = 45^\circ$  differs significantly from other angles. Ignition delay time becomes longer over a wide range of the incident radiant flux. This trend can be explained by two reasons: (1) the interaction between the vapor plume and the incident laser becomes less with the shallow incident angle. Since the ignition is believed to be caused by the absorption of the incident laser beam by the vapor plume, less interaction should increase ignition delay time. If this mechanism is correct, the minimum incident radiant flux for ignition will increase with a decrease in the incident angle. (2) The surface reflectance of the incident laser beam could increase with a decrease in the incident angle because of the increase in specular reflection. This reduces the amount of energy absorbed into decane and increases the ignition delay time and the minimum incident radiant flux for ignition. At present, without the results of reflectance measurements, it is not clear which mechanism controls the effect of the incident angle on ignition delay time. To extend the incident angle further, the relationship will be studied at  $30^\circ$  in the near future.

The results in Fig. 8a are converted into the log-log plot to find any characteristic relationship between the ignition delay time and the incident radiant flux. The plot is shown in Fig. 9. The important characteristic of this relationship is that it is non-linear in the log-log relation. A similar characteristic is also found for other incident angles. It indicates that there is more than one controlling process occurring as incident radiant flux is varied. One of the controlling processes might be the motion in decane caused by buoyancy.

The characteristic frequency of the fundamental mode of the internal wave caused by buoyancy is calculated as follows: Let  $\phi$  be velocity potential,  $z$  the axial coordinate and  $r$  the radial coordinate.

Then the governing equation becomes

$$\rho \left\{ \frac{\partial \phi}{\partial t} + \frac{1}{2} \vec{u}^2 + gZ \right\} + P - P_0 = 0 \quad (1)$$

Define  $\zeta$  as deflection of the surface caused by an internal wave.

Then, near  $Z = 0$

$$Z = \zeta(r, t)$$

At  $Z = 0$ , eq. (1) becomes

$$\rho \frac{\partial \phi}{\partial t} + \rho g \zeta = 0 \quad (2)$$

Since

$$\frac{\partial \zeta}{\partial t} = \frac{\partial \phi}{\partial Z}$$

eq. (2) becomes

$$\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial Z} = 0 \quad (3)$$

The solution of eq. (3) is

$$\phi = \cos(\omega t) \bar{\Phi}(r, Z) \quad (4)$$

Substitute this into eq. (3)

$$-\omega^2 \bar{\Phi} + g \frac{\partial \bar{\Phi}}{\partial Z} = 0 \quad \text{at } Z = 0$$

$$\text{at } Z = -h \quad \frac{\partial \bar{\Phi}}{\partial Z} = 0$$

$$\text{at } r = R \quad \frac{\partial \bar{\Phi}}{\partial r} = 0$$

Then, the eigen value  $\omega$  can be determined as

$$\omega^2 = \frac{g}{R} \lambda_n \tanh\left(\lambda_n \frac{h}{R}\right)$$

Since the frequency  $f$  is expressed as

$$f = \frac{\omega}{2\pi}$$

then,

$$f = \frac{1}{2\pi} \sqrt{\frac{g}{R} \lambda_n \tanh\left(\lambda_n \frac{h}{R}\right)} \quad (5)$$

For the fundamental mode,

$$\lambda_1 = 3.832$$

With  $R = 3$  cm and  $h = 5$  cm

$$f \cong 6 \text{ Hz}$$

Thus, the characteristic time of the fundamental mode of the internal wave is approximately 150 m sec. This indicates that, if ignition delay time is less than 150 m sec, the motion in decane is negligible and decane acts like a solid. However, if ignition delay time becomes longer than 150 m sec, it is long enough to start motion in decane. This might be the reason for the non-linear log-log relationship between ignition delay time and incident radiant flux as shown in Fig. 9.

Light emission from the flame measured by the photomultiplier shows an oscillating behavior after ignition. The temporal output of the photomultiplier is shown in Fig. 10a. It shows that the frequency of the oscillation is around 10 Hz. If the motion in the decane caused by the buoyancy causes this oscillation, the frequency becomes

$$f \sim \frac{1}{\sqrt{R}}$$

from eq(5), since the  $R$  dependency in the hyperbolic tangent term is negligible with the container size used in this study. Fig. 10b shows the photomultiplier output with a container of twice the diameter of



that used in Fig. 10a. No significant change in the oscillation frequency between them is observed. Therefore, the motion in the decane does not seem to cause the oscillation in the emission from the flame.

Another mechanism, which might cause the oscillation of the emission from the flame, is the interaction of the vapor plume and the incident laser beam in the gas phase. It can be explained as follows: vaporized decane from the surface is ignited by the absorption of the incident beam laser beam. Then, the long column of flame, which consists of combustion products, absorbs more incident radiation so that the energy into the decane is reduced. This reduces the amount of vapor and the size of flame column becomes smaller due to the consumption of the fuel vapor. The reduction in flame size reduces the absorption of the incident beam and increases energy into the decane. This increases the amount of decane vapor in the gas phase and the size of the flame becomes large. This process repeats and causes the oscillation of the flame size. If this mechanism causes the oscillation, the frequency of the oscillation should be sensitive to the incident angle of the beam which varies the interaction between the plume and the incident beam. Results at  $\theta = 45^\circ$  are shown in Fig. 10c. There are no significant differences from  $\theta = 90^\circ$  shown in Fig. 10a except the disappearance of high frequency components at  $\theta = 45^\circ$ . It indicates that the low frequency, large amplitude oscillation is not affected by the change in the incident angle. Therefore, it seems that the oscillation of the flame size is not caused by the interaction of the incident laser beam with the plume.

The frequency of the oscillation of the flame size observed in this study is almost the same as those observed in the burning of a solid fuel<sup>[1]</sup> and in a steady state gaseous diffusion flame.<sup>[2,3]</sup> The mechanisms of oscillation of these flames are tentatively explained as the

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<sup>1</sup>Figures in brackets indicate literature references at the end of this paper.



instability associated with complex flow pattern around the flame. From the measurements of Durao and Whitelaw<sup>[2]</sup> the instability was associated with inflection points in the local, instantaneous velocity distributions. Therefore, it seems that the observed flame oscillations might not be based on the characteristic of the present experimental configuration.

To obtain extinction coefficient of liquid decane, linear absorbance ( $\log I_0/I$ ) was measured by a Perkin-Elmer Model 180 Infrared Photometer using a variable length cell from wavenumber 1100 to 800  $\text{cm}^{-1}$ . Results are shown in Fig. 11 with various thicknesses of the cell. Extinction coefficient of decane can be calculated as

$$K = \frac{2.30}{l} \log \frac{I_0}{I} \quad (6)$$

where  $l$  is the thickness of the cell. However, Fig. 11 shows that the absorbance of the decane is sensitive to the wavenumber. Therefore, to obtain the extinction coefficient of decane, the finite width of the emission spectra of the  $\text{CO}_2$  laser cannot be neglected although the width is much narrower than that of a blackbody. Then, total extinction coefficient becomes

$$\tilde{K} = \frac{1}{l} \ln \left[ \frac{\int_{\nu_1}^{\nu_2} I_0(\lambda) d\lambda}{\int_{\nu_1}^{\nu_2} I_0(\lambda) e^{-K_\lambda l} d\lambda} \right] \quad (7)$$

The emission spectra of the  $\text{CO}_2$  laser will be measured in the future.

Assuming the single line of 946  $\text{cm}^{-1}$  as  $\text{CO}_2$  laser line, the calculated extinction coefficient of decane is 16  $\text{cm}^{-1}$  which is much smaller than about 90  $\text{cm}^{-1}$  of solid polystyrene.<sup>[4]</sup> Therefore, the laser beam penetrates further into the decane and heats a larger volume of the decane than the polystyrene. This is one of the reasons why the decane requires higher incident flux for ignition and its ignition delay time is longer than polystyrene.

#### 4. Future Plans

- (a) To measure surface reflectances and extinction coefficients of decane and JP-5 fuel at  $\text{CO}_2$  laser wavelengths.
- (b) To complete the measurement of the relationship between the ignition delay time and the incident radiant flux at the incident angle of  $30^\circ$ .
- (c) To take high speed shadowgraph pictures to observe the development of the vapor plume in the gas phase.
- (d) To investigate the measurement technique of decane vapor concentration using a massspectrometer.
- (e) To develop time dependent one-dimensional heat conduction model including radiative transfer.

#### REFERENCES

1. Private communication with Merwin Sibulkin.
2. Durao, D.F.G., and Whitelaw, J.H., Proc. Roy. Soc. A338, 479 (1974).
3. Grant, A.J., and Jones, J.M., Comb. Flame, 25, 153 (1975).
4. Ohlemiller, T.J., and Summerfield, M., The Thirteenth Symposium (International) on Combustion, 1087 (1971).

## FIGURES

- Fig. 1 Schematic illustration of experimental apparatus.
- Fig. 2 Picture of overall experimental apparatus.  
A-CO<sub>2</sub> laser, B-Mirror, C-Mirror, D-Chamber, E-Safety Shield.
- Fig. 3 Picture of Chamber.  
A-photomultiplier, B-Chamber, C-Chamber rotation worm gear.
- Fig. 4 Schematic illustration of apparatus to measure total reflectance.
- Fig. 5 The effect of the container depth on ignition delay time.
- Fig. 6a, 6b. The effect of the container diameter on ignition delay time.
- Fig. 7 High speed pictures of the onset of ignition followed by flame propagation. 1500 frames/sec.  $I_0 = 1900 \text{ W/cm}^2$ ,  $\theta = 60^\circ$ .
- Fig. 8 The relationship between the ignition delay time and the incident radiant flux. (a)  $\theta = 90^\circ$ , (b)  $\theta = 75^\circ$ , (c)  $\theta = 60^\circ$ , (d)  $\theta = 45^\circ$ .
- Fig. 9 The log-log relationship between the ignition delay time and the incident radiant flux at  $\theta = 90^\circ$ .
- Fig. 10 Timewise change in photomultiplier output at  $I_0 = 4000 \text{ w/cm}^2$ .  
(a)  $\theta = 90^\circ$ ,  $D = 5\text{cm}$ , (b)  $\theta = 90^\circ$ ,  $D = 10\text{cm}$ , (c)  $\theta = 45^\circ$ ,  $D = 5\text{cm}$ .
- Fig. 11 Spectra of linear absorbance of decane.  
(a) cell only, (b)  $\ell = 0.1$ , (c)  $\ell = 0.25$ , (d)  $\ell = 0.5$ ,  
(e)  $\ell = 0.75$  and (f)  $\ell = 1.0\text{mm}$ .



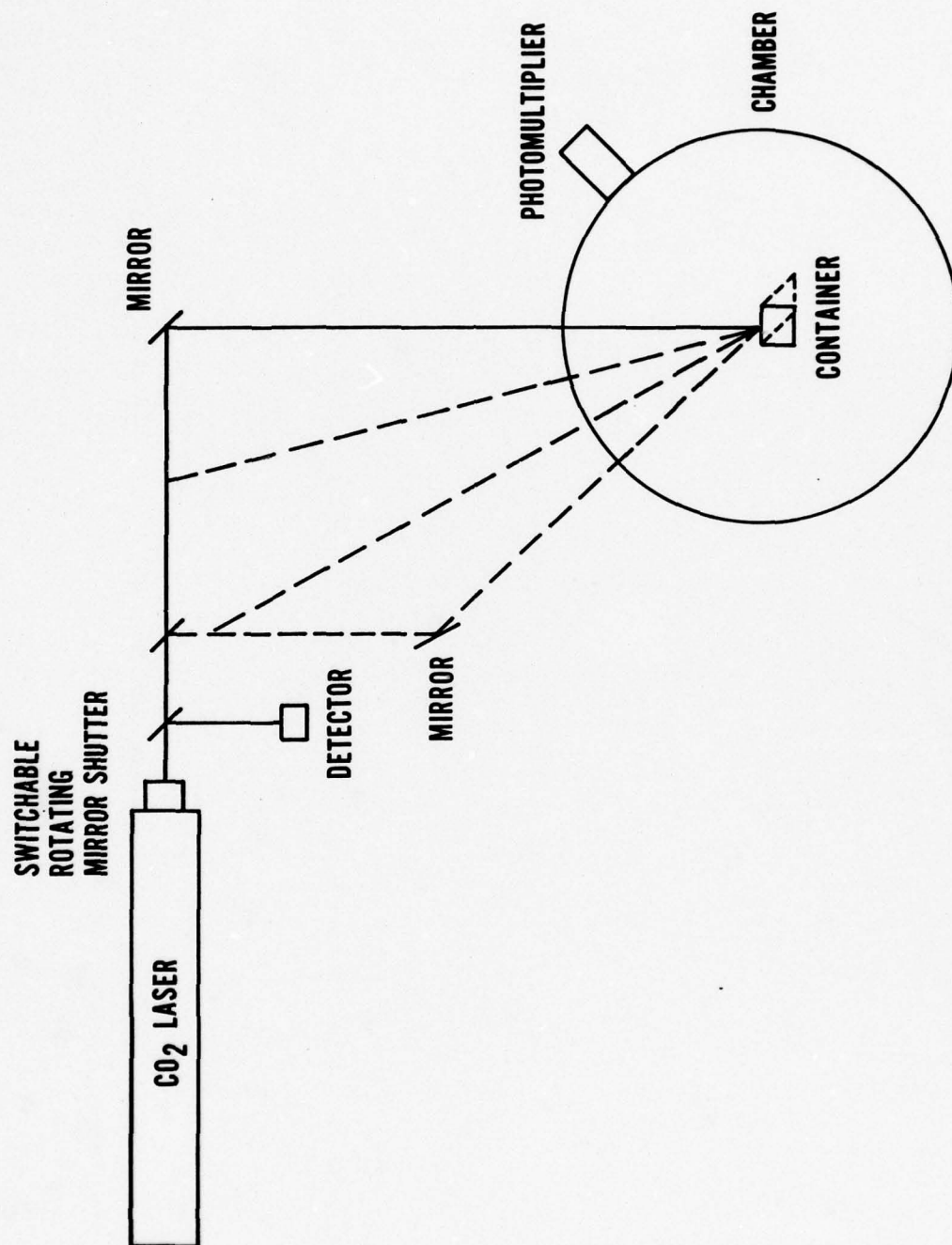


Figure 1

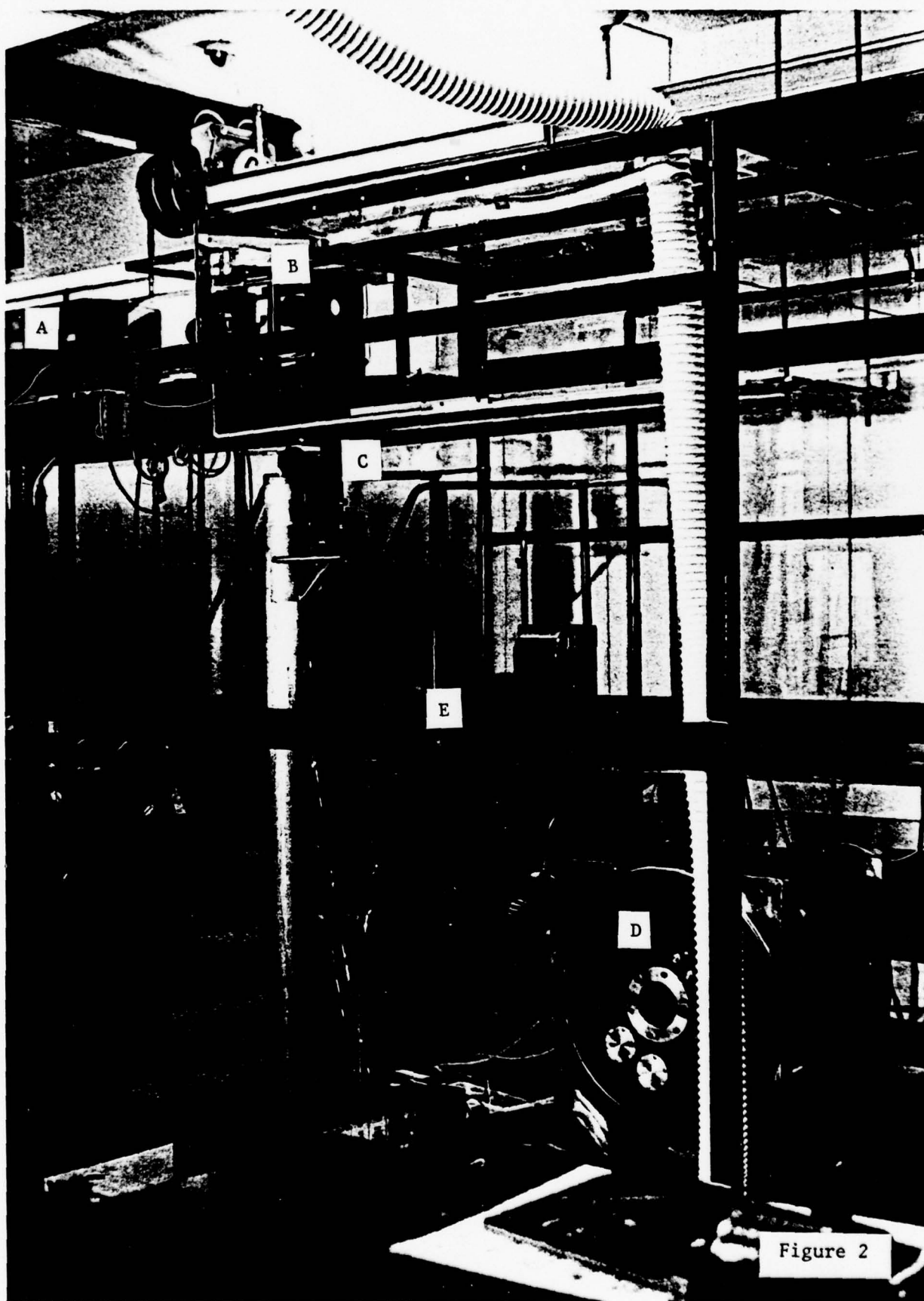


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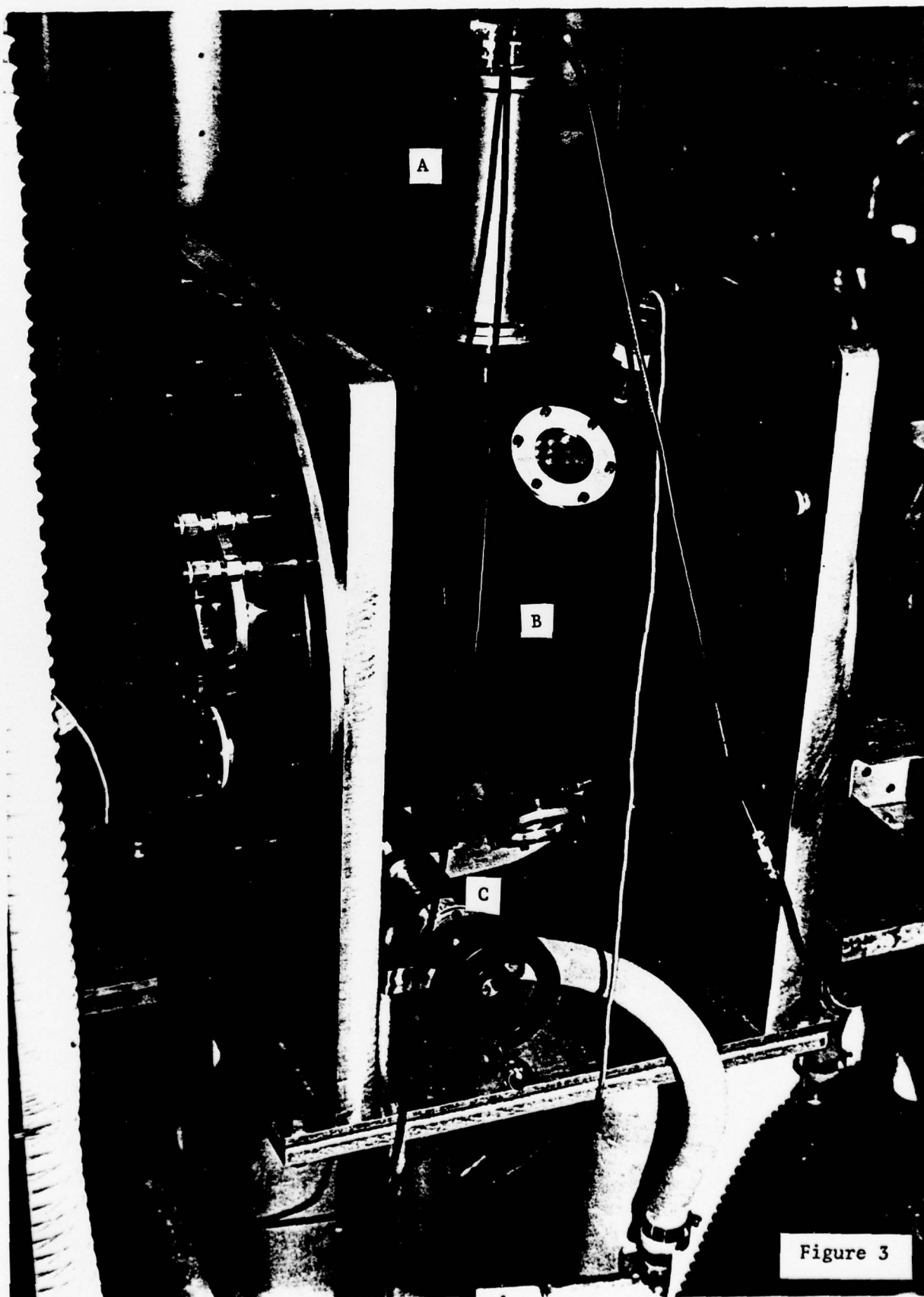


Figure 3

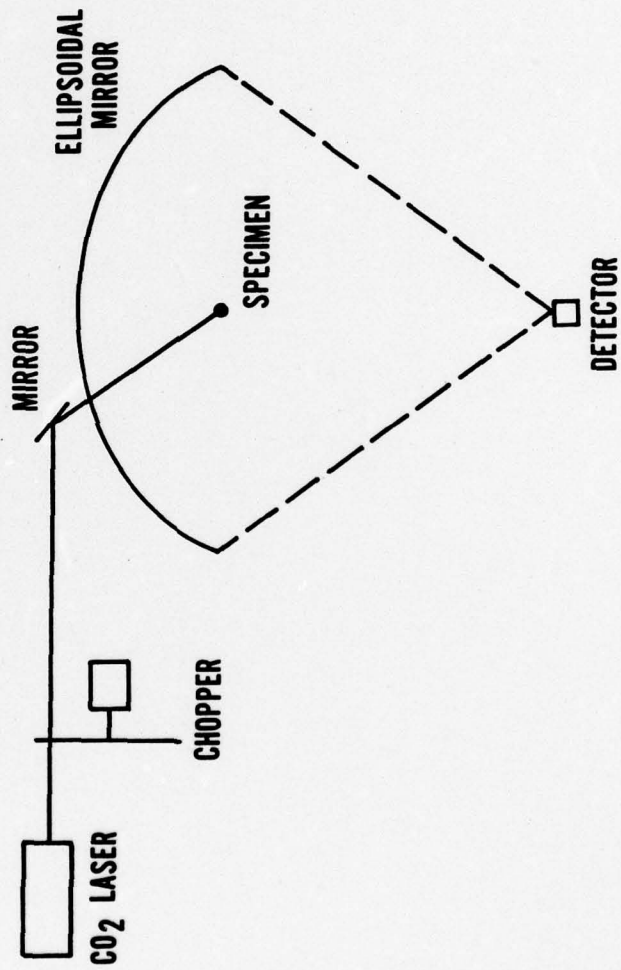


Figure 4



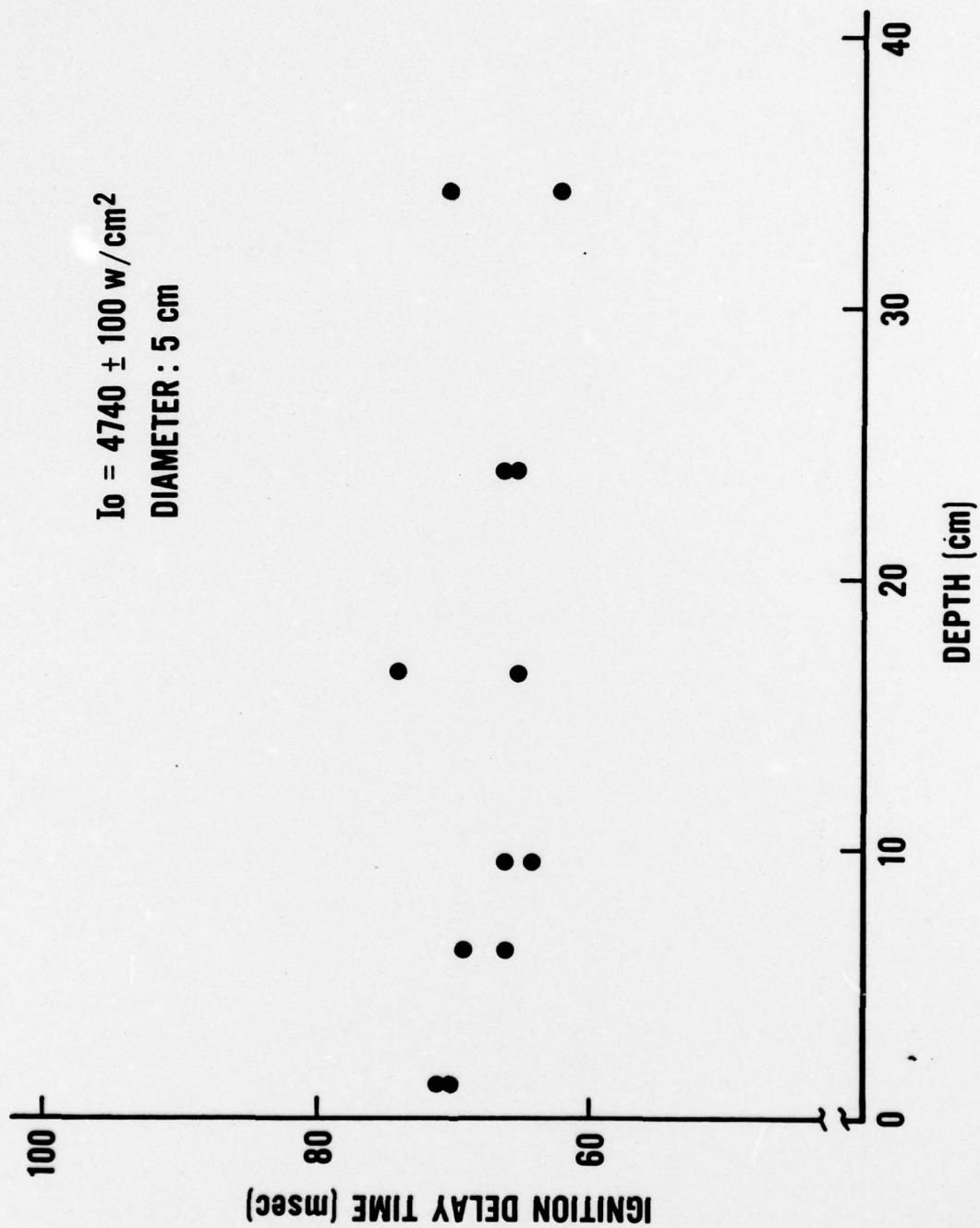


Figure 5

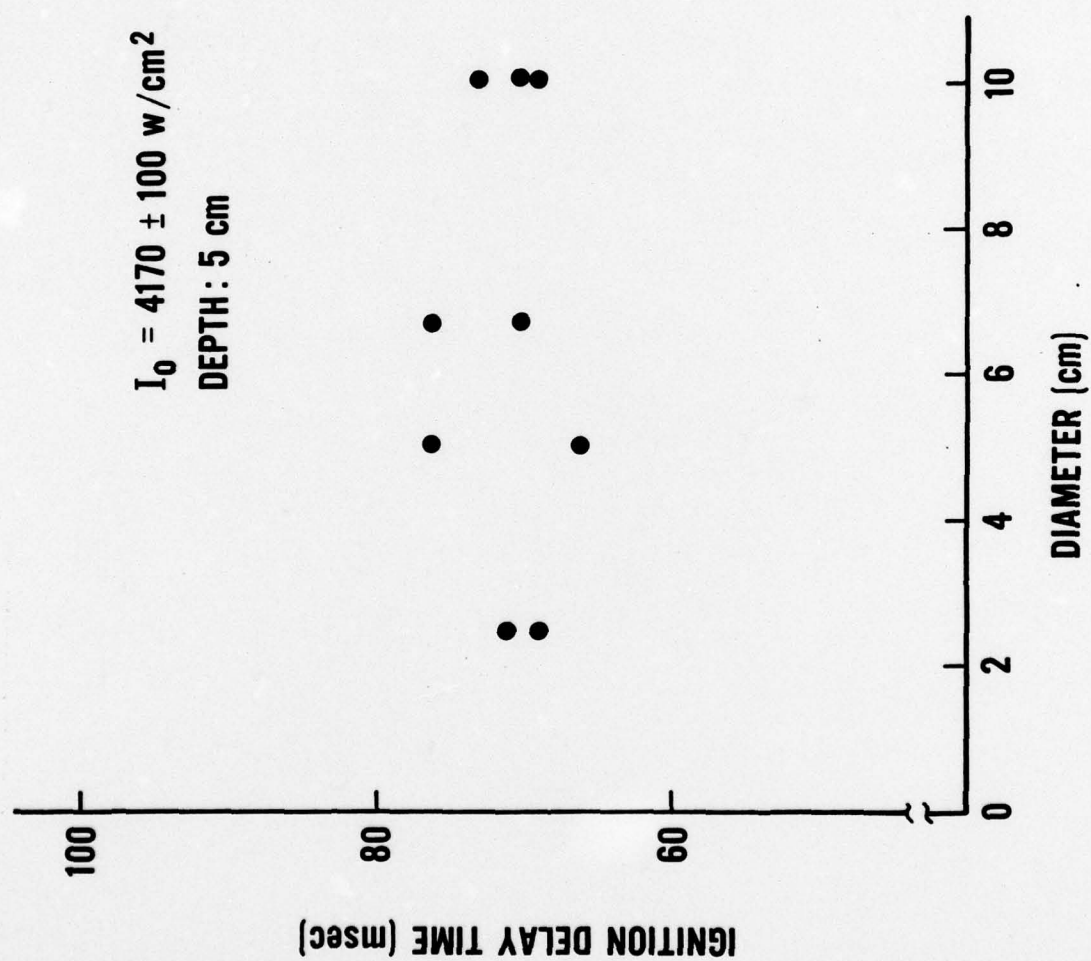


Figure 6a

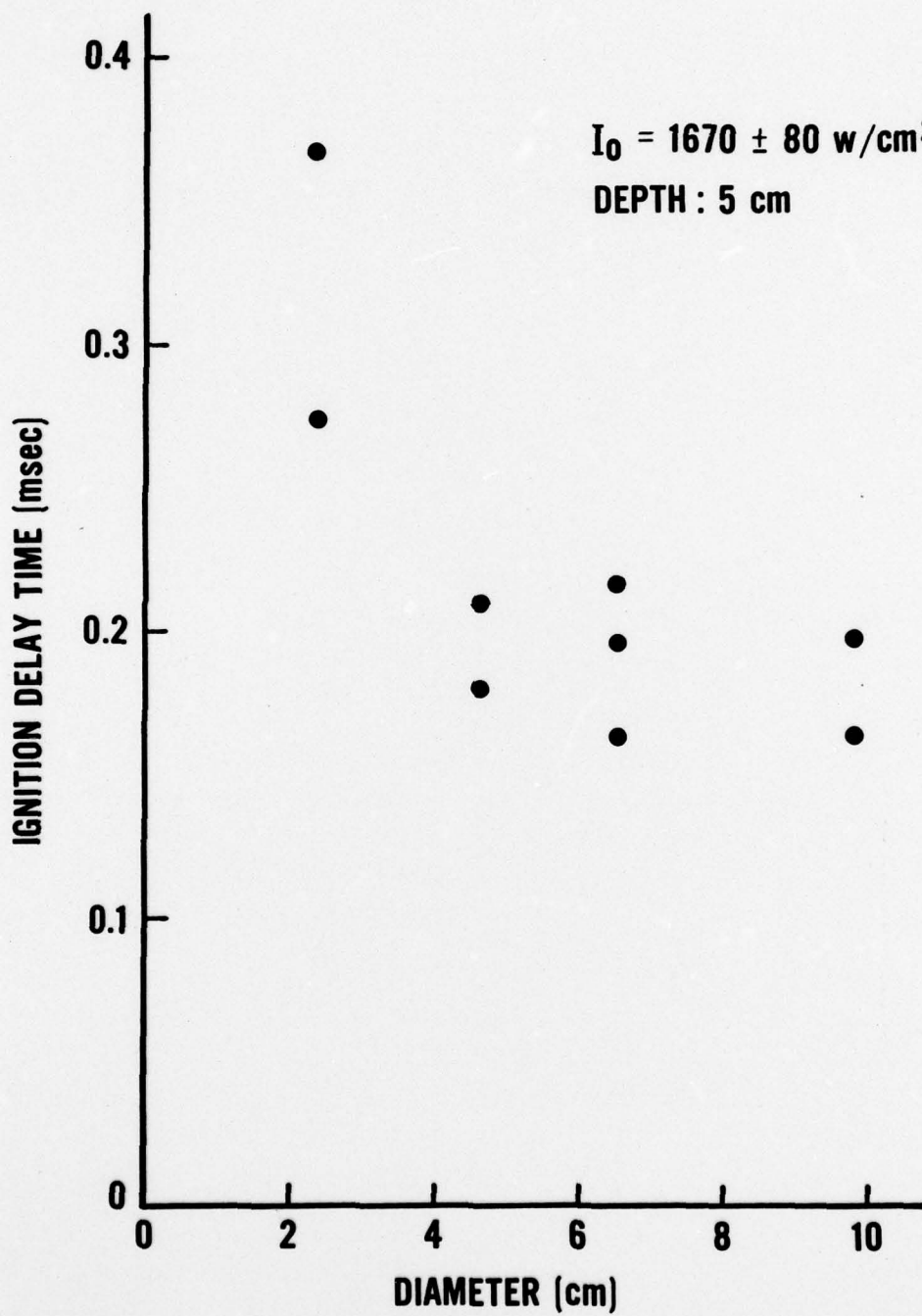


Figure 6b



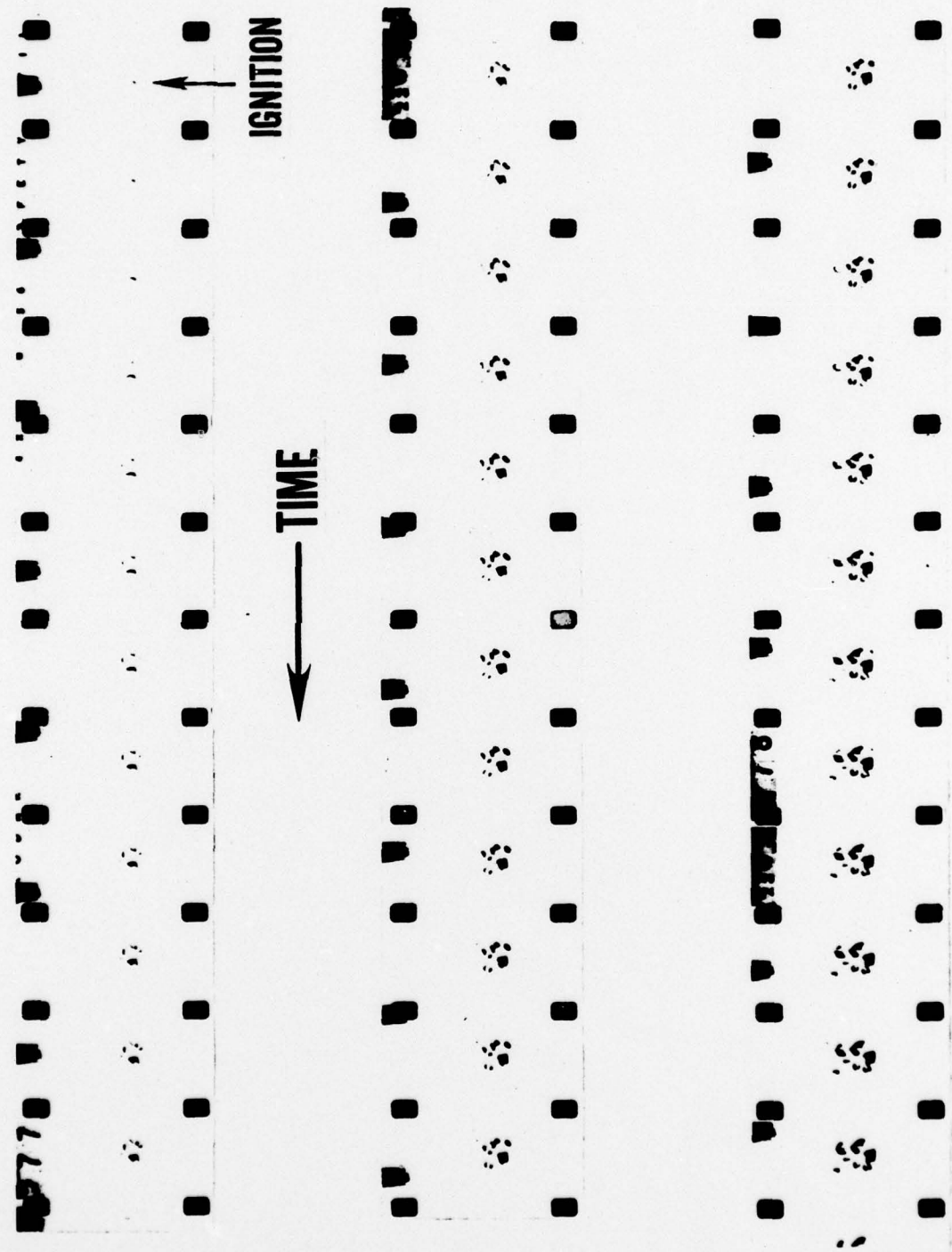


Figure 7

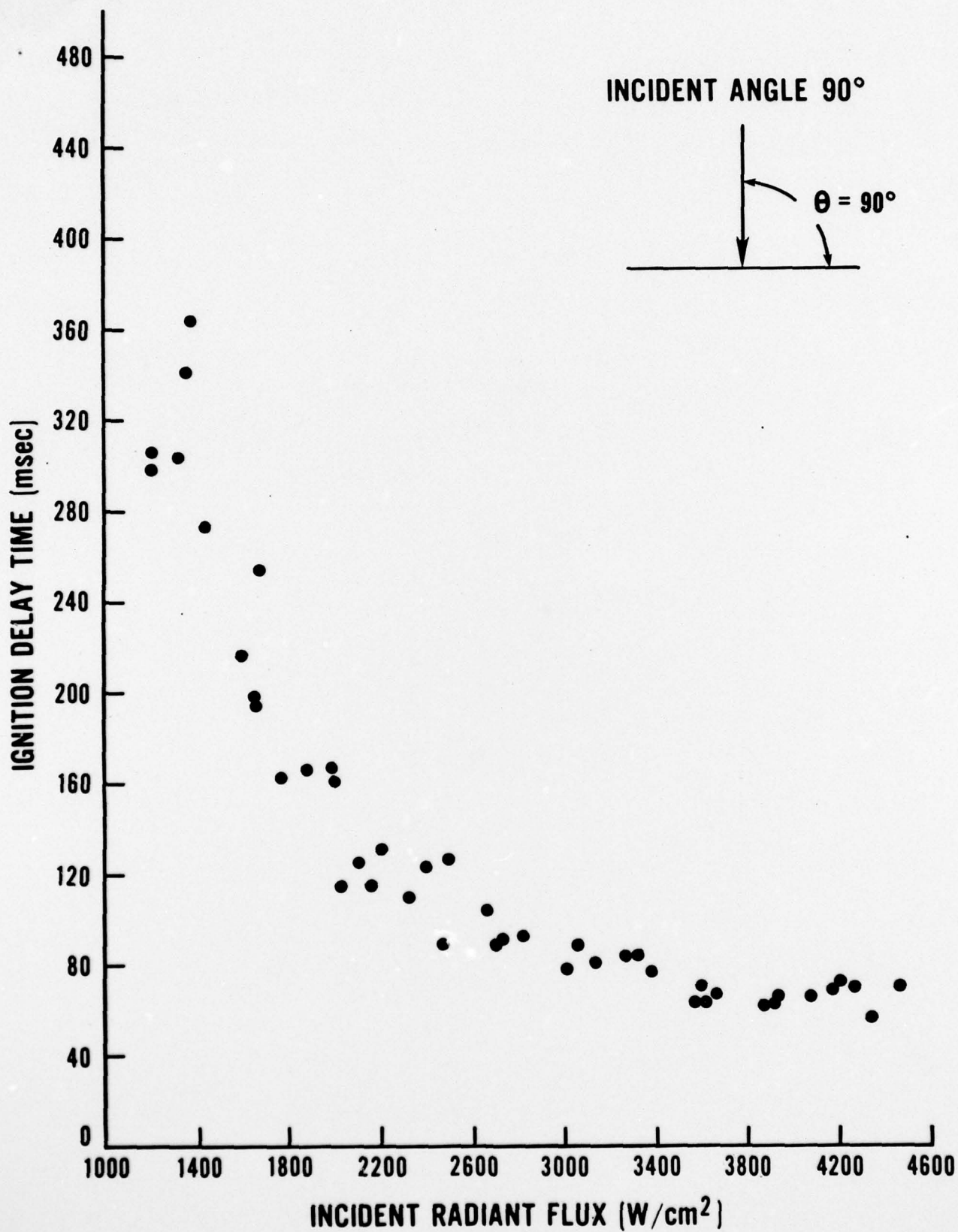


Figure 8a

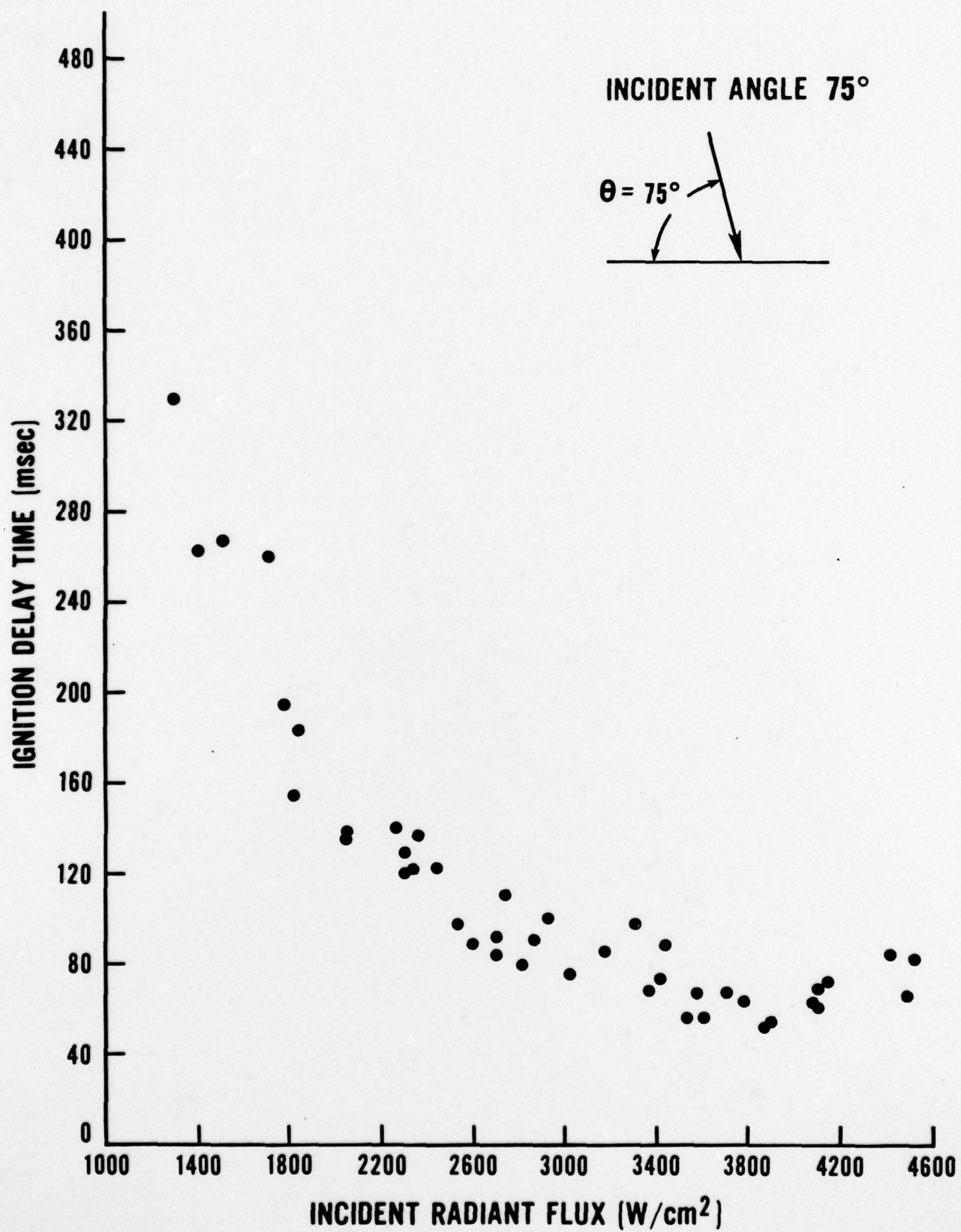


Figure 8b



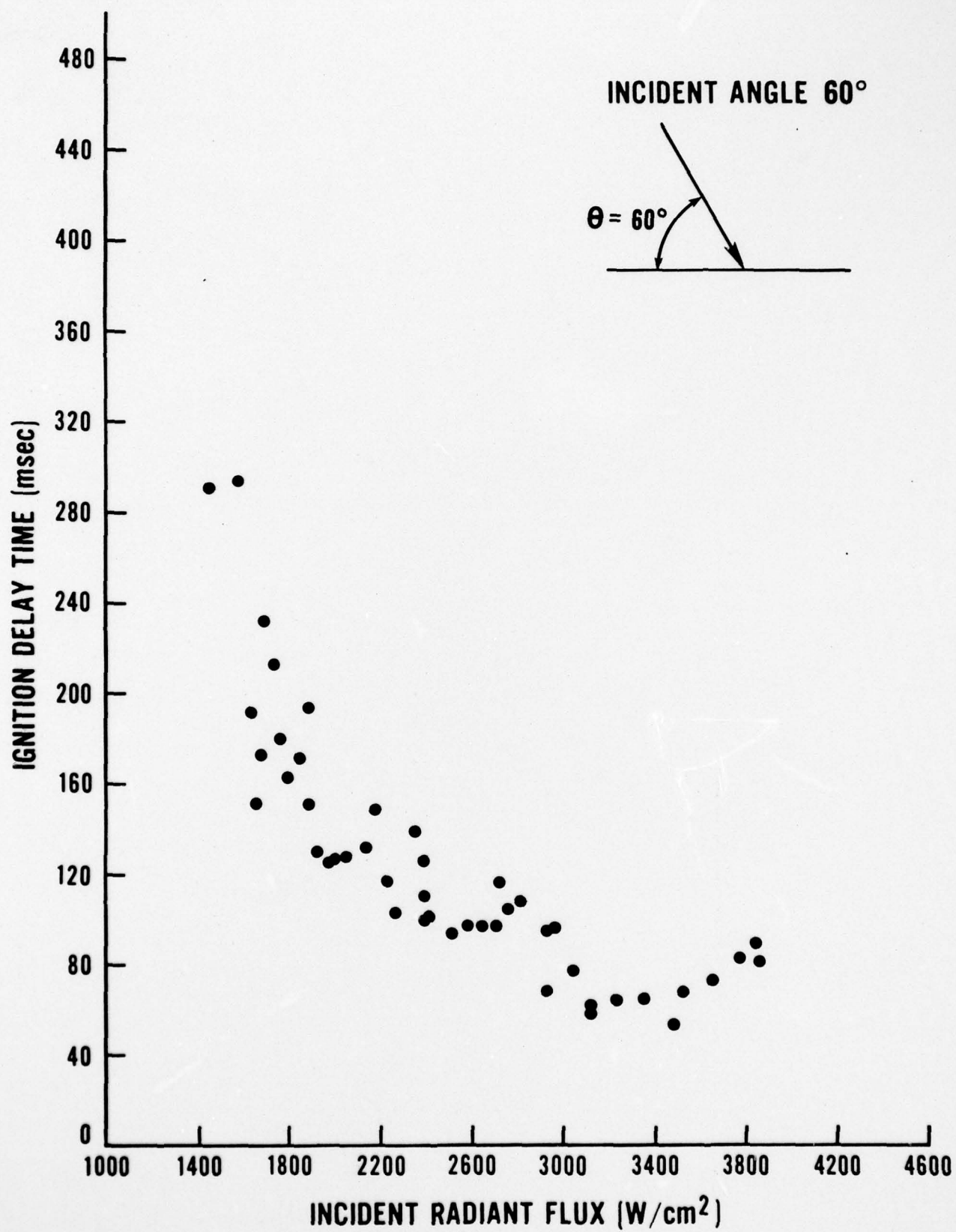


Figure 8c

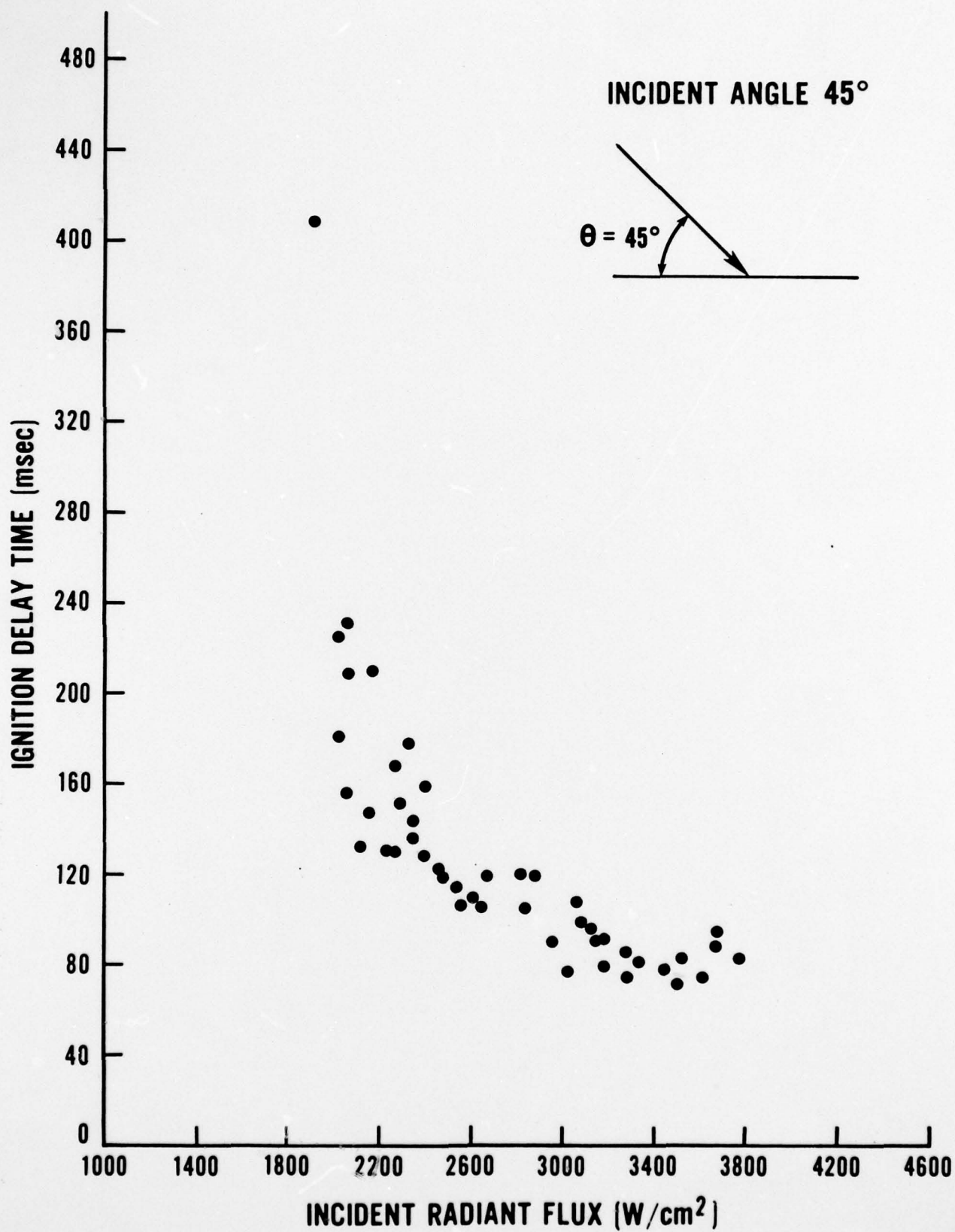


Figure 8d

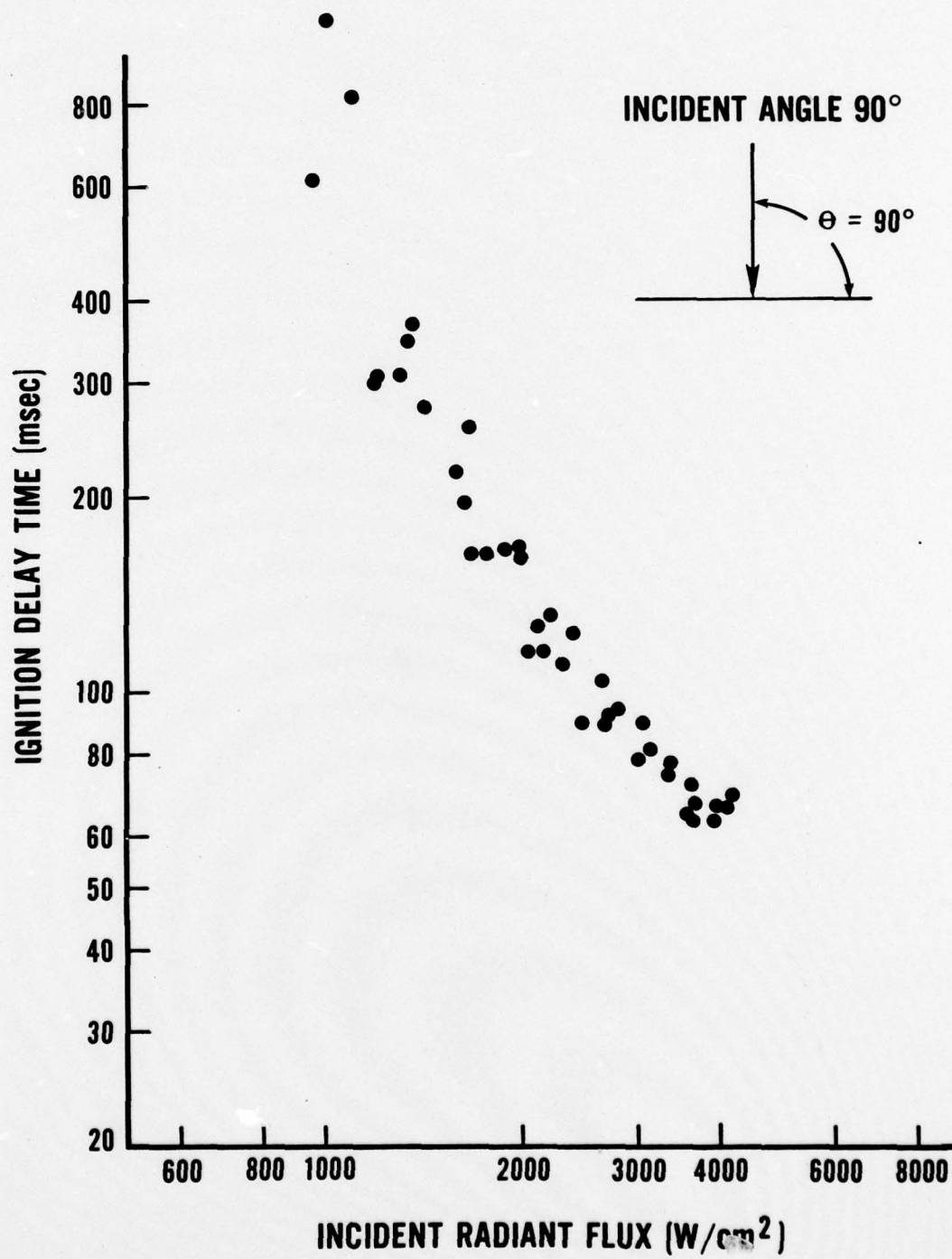


Figure 9



INCIDENT ANGLE  $\theta = 90^\circ$

$D = 5 \text{ cm}$

0.1 sec

TIME



Figure 10a

INCIDENT ANGLE  $\theta = 90^\circ$   
 $D = 10 \text{ cm}$

0.1 sec

TIME

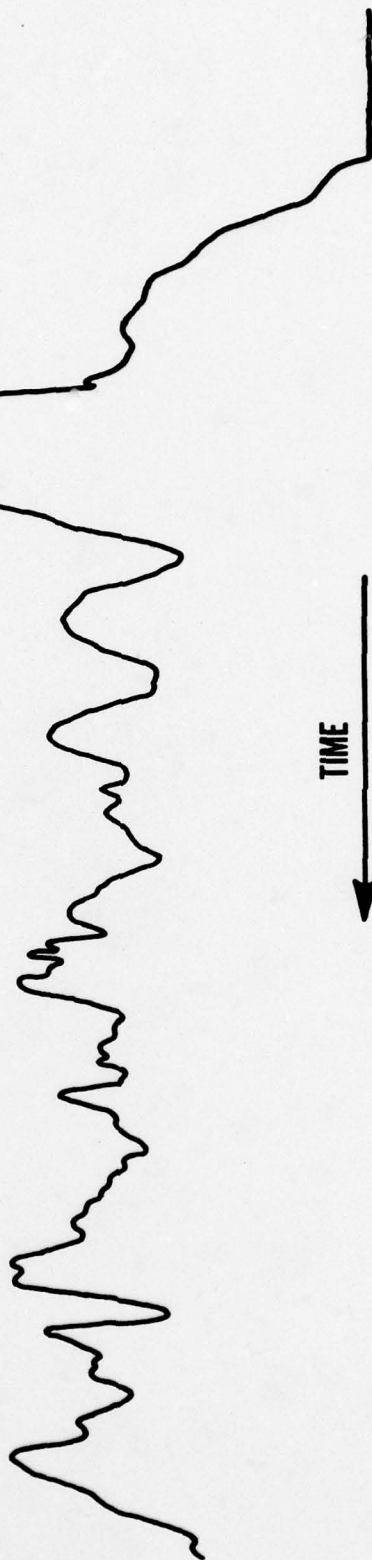


Figure 10b

INCIDENT ANGLE  $\theta = 45^\circ$   
 $D = 5 \text{ cm}$

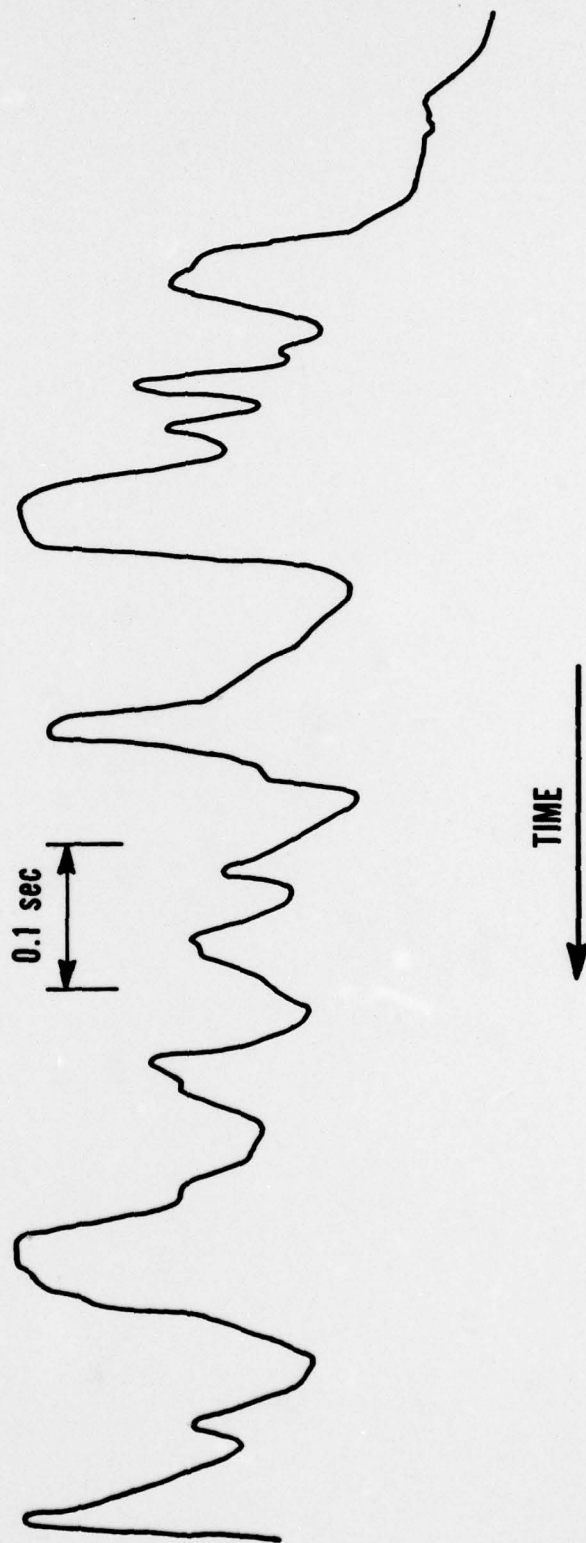


Figure 10c



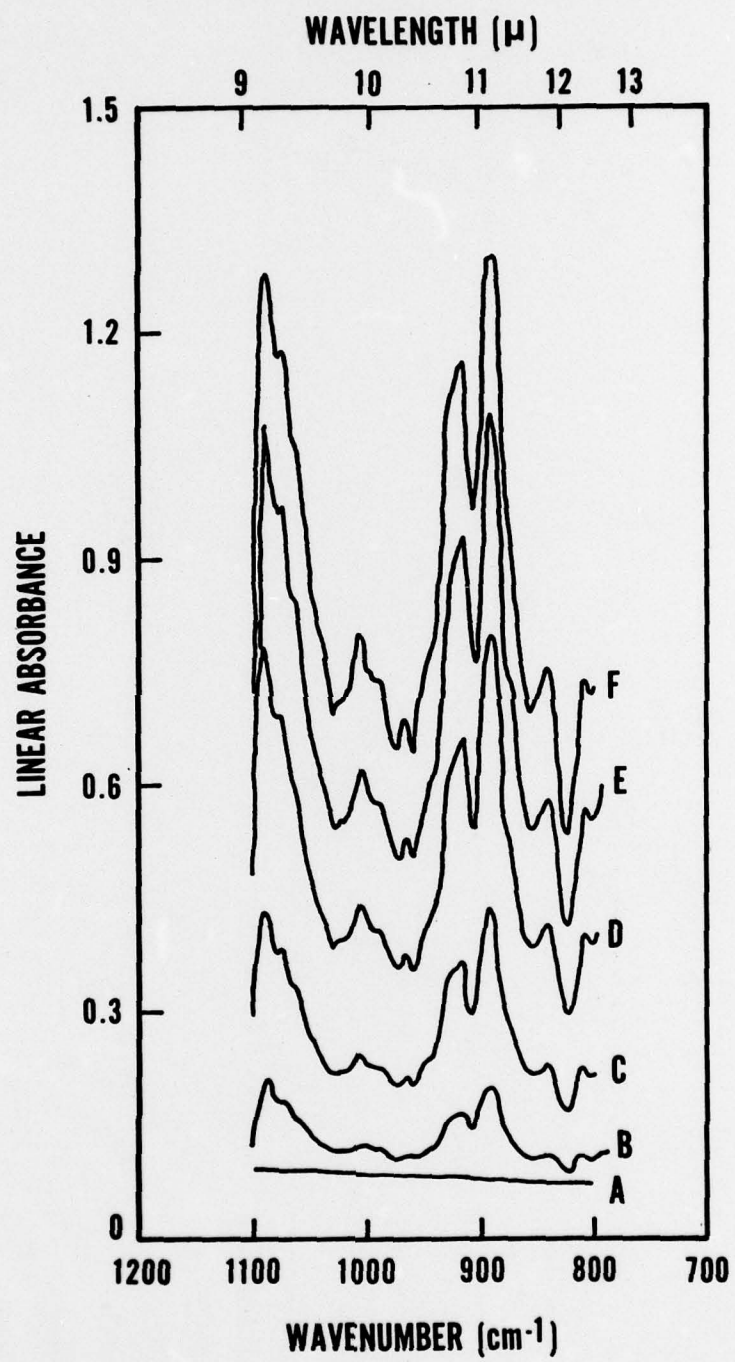


Figure 11

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